

Developing a Regional Framework for Assessing Coastal Vulnerability to Sea Level Rise in Southern New England

Part 1

**A Case Study from The Nature Conservancy
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Project Overview

Coastal environments contain some of the most dynamic ecosystems in the world, and obtaining and integrating the most up-to-date and accurate digital elevation data continues to be a fundamental challenge for coastal resource managers. Because sea level rise (SLR) is predicted to intensify the problems caused by waves, storm surge, shoreline erosion, wetland loss, and saltwater intrusion, the ability to accurately identify low-lying lands is a critical factor for assessing the vulnerability of coastal regions (Gesch and others 2009).

Southern New England faces a number of impacts resulting from SLR, including habitat fragmentation, habitat conversion, complete loss of certain coastal ecosystems and species, and threats to human communities. Assessing the vulnerability of natural and human communities from SLR is critical in planning for and adapting to the effects of climate change. To accomplish this, a critical first step is obtaining comprehensive elevation and other coastal zone information. These data, however, are often not available at resolutions needed to make state and regional governance decisions about climate issues. In the absence of such information, coastal managers may struggle when making required adaptation-planning decisions to protect communities and to provide solutions that incorporate both developed and natural infrastructure.

Projections of SLR over the course of the 21st century vary depending on factors such as the type of model used, future emissions scenarios, the degree to which rapid polar ice sheet breakdown is considered, and local effects such as land subsidence. The Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment projected a rise of 0.2 to 0.6 meters by the year 2100 unless greenhouse gas emissions are reduced substantially (IPCC 2008). In addition, the IPCC did consider the possibility of “rapid changes” by scaling up the ice discharge by adding 0.1 to 0.2 m to their higher estimates. However, this does not incorporate potential effects of dynamic processes that can further accelerate ice losses (IPCC 2007). Greenland and West Antarctic ice sheets, which may contribute significantly to projected rise, contain enough ice to raise sea level by 7 meters and 3.3 meters, respectively, if melted completely (Bamber and others 2009). Recent studies (Hu and others 2009, Yin and others 2009) modeling ocean currents in response to climate change predicts that the Northwest Atlantic will experience even higher sea levels than the global average because of anticipated slowdowns of ocean currents in response to global warming. It is also important to point out that even with stabilization of global temperatures sea level is expected to continue to rise for centuries.

The primary purpose of this study is to highlight both the limitations and opportunities of mapping SLR at regional scales and therefore determine whether this information can influence the development of ecosystem-based adaptation strategies. With this study, The Nature Conservancy (TNC) and its partners hope to add value to the growing field of coastal resilience and adaptation planning.

The geographic scope of the study is Southern New England extending from Cape Cod, Massachusetts, to Long Island, New York (Figure 1). Working with the National Oceanic and Atmospheric Administration (NOAA) Coastal Services Center and the U.S. Geological Survey (USGS), TNC has examined available topographic information consisting of both national- and regional-scale data and assessed the accuracy of disparate elevation data sets. The NOAA Coastal Services Center provided data, expertise, and technical assistance in analyzing and utilizing the elevation data, and

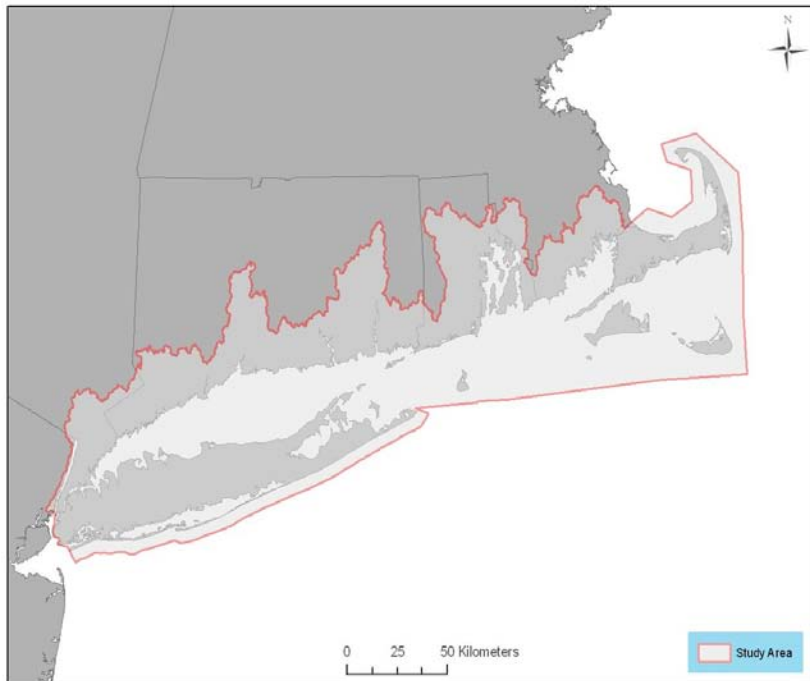


Figure 1. Project study area.

served as a strategic advisor for how to apply these data, methods, and approaches to mapping SLR at regional scales to coastal management issues. Much of the methodology was based on previous studies undertaken by USGS staff members. Additionally, USGS staff members served as advisors to this project with regard to elevation data integration and SLR mapping methods. TNC has also partnered with the Center for Climate Systems Research (CCSR) at Columbia University and the NASA Goddard Institute for Space Studies to offer advice on SLR projections, given the available data and matching SLR projections appropriate to the accuracy and resolution of the elevation data.

This project accomplished the following:

- Evaluated potential improvement of a seamless regional elevation data set that was currently available (i.e., the National Elevation Dataset, or NED, from USGS) and then compared the mapping of inundation zones using two different approaches to integrating elevation data
- Determined achievable SLR projections at which we could accurately and realistically map zones of inundation and then mapped SLR while spatially illustrating uncertainty into our mapped inundation zones

The Process

The process involved in constructing a regional elevation framework to examine coastal vulnerability and adaptation to SLR was twofold:

1. Evaluate two different integrated elevation data approaches to be used for regional, multi-state SLR inundation mapping.
 - a. Multi-state seamless National Elevation Dataset (NED)
 - b. Multi-state improved seamless elevation data using a combination of NED and lidar data
2. Determine the SLR value to map that is appropriate based on the elevation data accuracy. We calculated the relative vulnerability of different coastal areas to a 1-meter SLR. We employed proven approaches for spatially illustrating inundation uncertainty as determined by digital elevation model (DEM) accuracy (see Gesch 2009, for example). The relative vulnerability calculation was determined by the percentage of land equal to or less than the 1-meter elevation within 1 kilometer of the shoreline.

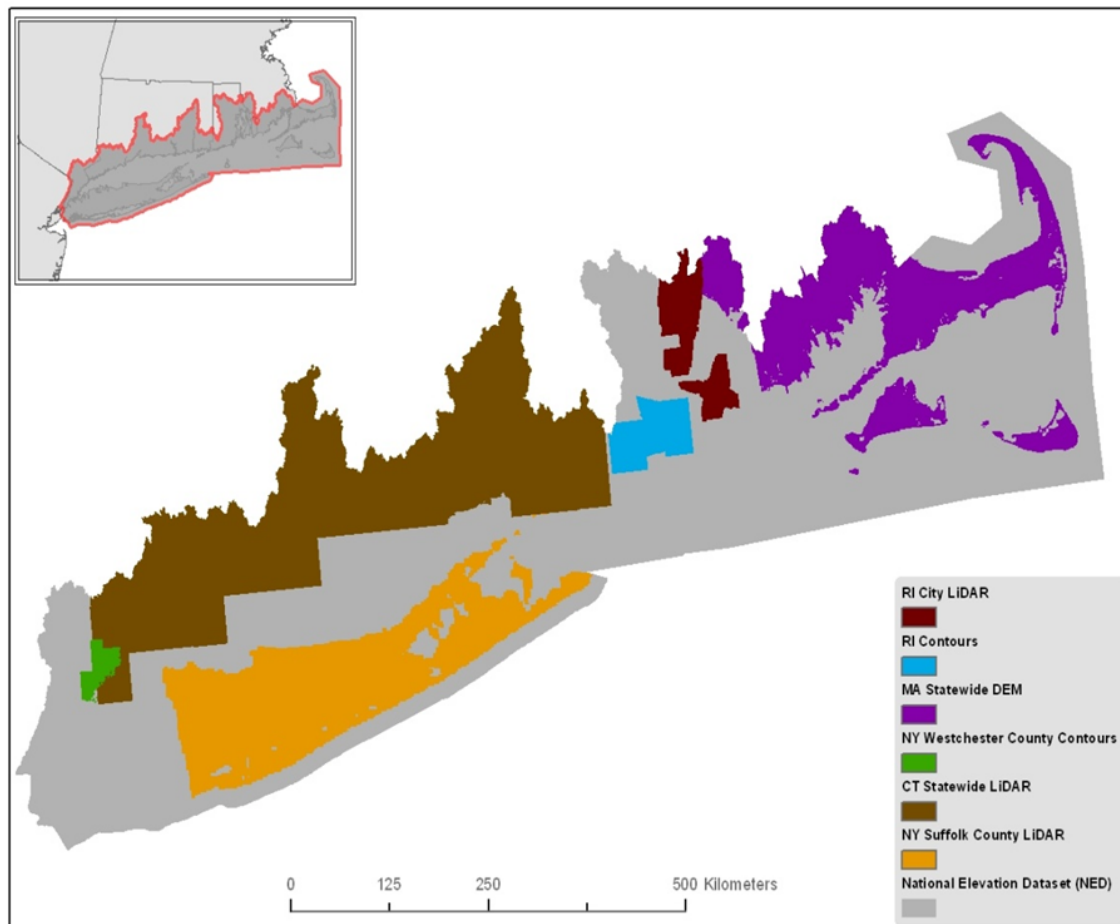
Examining Integrated Elevation Data Approaches

Coastal elevation data have been widely used to quantify the potential effects of SLR; however, the accuracy of the elevation data directly affects the quality and utility of SLR impact assessments (Gesch 2009; Poulter and Halpin 2008; Titus and Wang 2008; Najjar and others 2000; Kleinosky and others 2007; Titus and Richman 2001). Broad-scale (regional and national) delineation of lands vulnerable to SLR using the best-available elevation data often requires integration of state and local data, since the best-available national data set, the USGS's NED data, does not always include the most up-to-date information. It is especially important to incorporate the most recent elevation data because of the dynamic nature of coastal processes and the rapid pace of development along coastal regions. This is particularly critical in the Southern New England study area, since it contains some of the most highly urbanized estuaries in the United States, such as Long Island Sound, with approximately 8 million people living within the watershed (EPA Long Island Sound Study 2007).

The vertical accuracy of the NED has also been found to be inadequate for mapping local, low-level inundation estimates and thus has been deemed unsuitable for local and even regional decision-making (Titus and Wang 2008; Gesch 2009). In the United States, local and state agencies typically collect and maintain the most up-to-date and accurate elevation data, but coastal managers often have trouble effectively integrating these data with federal data due to inconsistent geospatial frameworks such as varying projections, datums, and data formats (Gesch and Wilson 2002). Nonetheless, many regional and national studies of coastal environments require seamless topographic data, since hydrologic, demographic, and ecological processes often go beyond the limits of municipal or state boundaries. If forced to choose, many coastal managers have also noted that they favor data consistency over data accuracy for many of their applications (NOAA Coastal Services Center *personal communication* 2009; Gesch and Wilson 2002).

TNC gathered existing digital elevation data that included lidar and other data sets, such as the NED, where high-resolution lidar data were not available, from a range of federal, state, and local government agencies. TNC integrated multi-scale, multi-source elevation data sets for the

purposes of SLR inundation mapping using an innovative method developed by Gesch and Wilson (2002) (Figure 2). This method was employed in an attempt to improve the best-available regional seamless elevation data set by integrating the most up-to-date high-resolution local elevation data, where applicable.



Dataset	Format upon acquisition	Vertical Accuracy (RMSE)	Horizontal Resolution
National Elevation Dataset (NED)	Grid DEM (multiple sources)	2.44 m	10 m
CT LiDAR	Grid DEM (LiDAR derived)	68 cm	3 m
MA DEM	Grid DEM (photogrammetrically derived)	1.5 m	5 m
NY Suffolk County DEM	Grid DEM (LiDAR derived)	13 cm	1.5 m
NY Westchester County Contours	Contour Lines (photogrammetrically derived)	60 cm	5 m
RI Contours	Contour Lines (photogrammetrically derived)	20 cm	3 m
RI City DEM	Grid DEM (LiDAR derived)	9 cm	1 m

Figure 2. Location, specifications, and types of data collected, and which agencies provided them.

Mapping Coastal Inundation

Many types of elevation data sets have been used in previous studies to quantify the potential inundation from SLR (see Gesch and others 2009). Poulter and Halpin (2008) detail the various approaches used to model SLR, ranging from the “bathtub fill” approach to inundating lands that are hydrologically connected to the ocean. The bathtub fill approach simply fills low-lying elevation points. Often this method can create erroneous inundated areas that are not connected to the ocean as all areas equal to or below the given SLR interval become inundated, therefore creating “islands” of inundation. The hydrologically connected approach forces coastal inundation to occur only where low-lying elevation is hydrologically connected to the ocean. It is worth noting that Gesch 2009 stated as follows, “[the] development of large-scale spatially explicit maps presents a new set of challenges. At scales useful for local decision-making, the hydrological connectivity of the ocean to vulnerable lands must be mapped and considered.” Though we are in full agreement with this assertion, the time required to adequately condition the DEM to allow for accurate hydrological connectivity was beyond the scope of this project. In light of the importance of hydrologic connectivity, many newer data sets are being developed to force proper water flow.

We used the bathtub fill approach to identify the most vulnerable lands for a 1-meter SLR. It was determined that 1 meter was the appropriate SLR interval to map based on the accuracy of the elevation data. In other words, mapping levels smaller than 1 meter could not be supported by the data, given the data’s

vertical accuracy. After mapping 1 meter of SLR, we calculated relative vulnerability within discrete coastal regions (coastal shoreline units, shown in Figure 3 and described in Part 2 of this case study). Relative vulnerability was determined by calculating the percentage of land equal to or less than 1 meter in elevation within one kilometer of the shoreline. To compare each coastal region’s relative vulnerability to SLR, a distance from the shoreline was needed to calculate the percentage of land inundated for each coastal

shoreline unit. Because this study is focused on coastal human and natural communities affected by SLR, therefore those located in close proximity to shorelines, and because 1 meter of SLR inundation never expanded landward more than 1 kilometer in our study area, we restricted this relative vulnerability calculation to areas within 1 kilometer of the shore. This

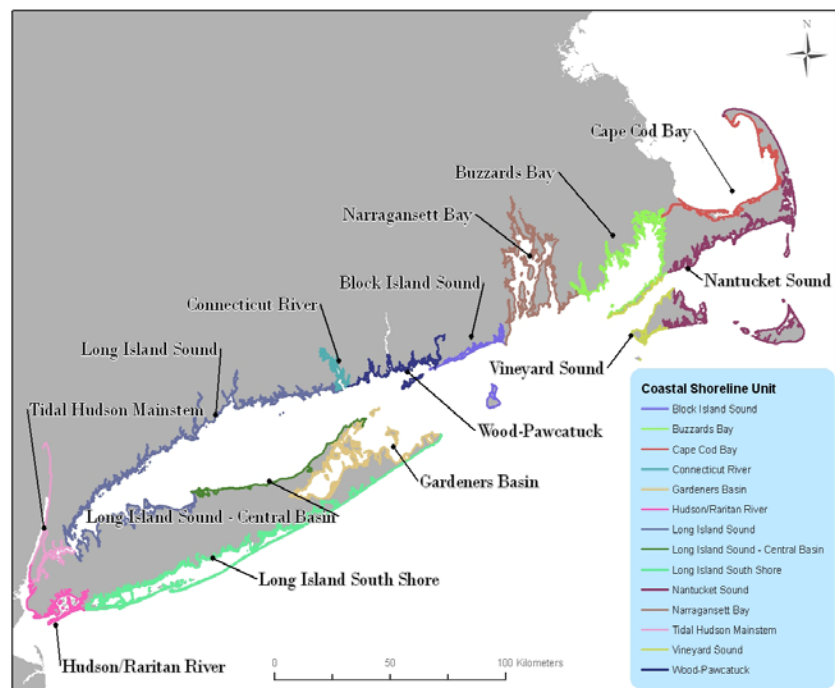


Figure 3. Coastal Shoreline Units

metric is not intended to be interpreted as an absolute percentage of land inundated within one kilometer; instead this should be interpreted as a general metric that helps identify which coastal regions are most vulnerable to a 1-meter SLR throughout Southern New England.

Finally, expanding on recent work by Gesch (2009), we mapped a 1-meter SLR scenario using new methods to spatially illustrate the uncertainty of SLR inundation maps as determined by the input elevation data's vertical accuracy.

Results and Implications

Elevation Data Approaches

We incorporated attainable local and state high-resolution elevation data into the best currently available seamless multi-state elevation data set, the National Elevation Dataset (NED). Based on an independent accuracy assessment using U.S. Geological Survey benchmarks, the multi-state seamless elevation data approach from multiple sources was 55% (or 1.25 feet) more accurate than the NED alone (Figure 4). Although this integrated approach proved to be successful throughout most of the study area, several areas failed to integrate adjacent data sets of contrasting sources and accuracies. Errors were discovered in cases where two data sets of vastly differing accuracies were brought together (Figure 5). In these areas we found that, although the reported accuracy of the lidar data set in question was very high, several errors in the data set had likely occurred during the lidar point classification process. Since we acquired this data set from the end-user in raster format, and not from the source of the data, we were unable to correct these errors. We therefore suspect that this lidar data set compounded the errors when combining it with the much coarser NED. Thorough examination of lidar is important here, and one cannot assume that lidar is free of errors because it is of high spatial resolution. Careful examination of high-resolution data is also critical to mapping SLR accurately. We therefore recommend that users use caution when combining coarse data sets such as the NED with high-resolution lidar, since the blending procedure can create more errors in the integrated DEM than might be found in the NED without integration.

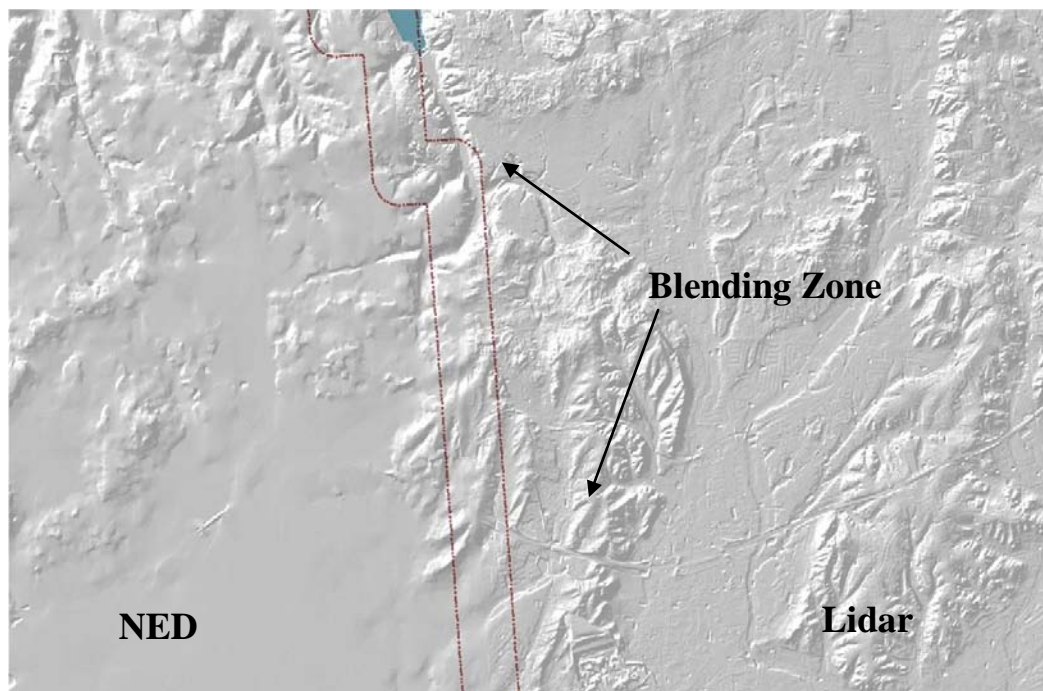


Figure 4. Accuracy assessment between multiple-source lidar data set and the NED alone.

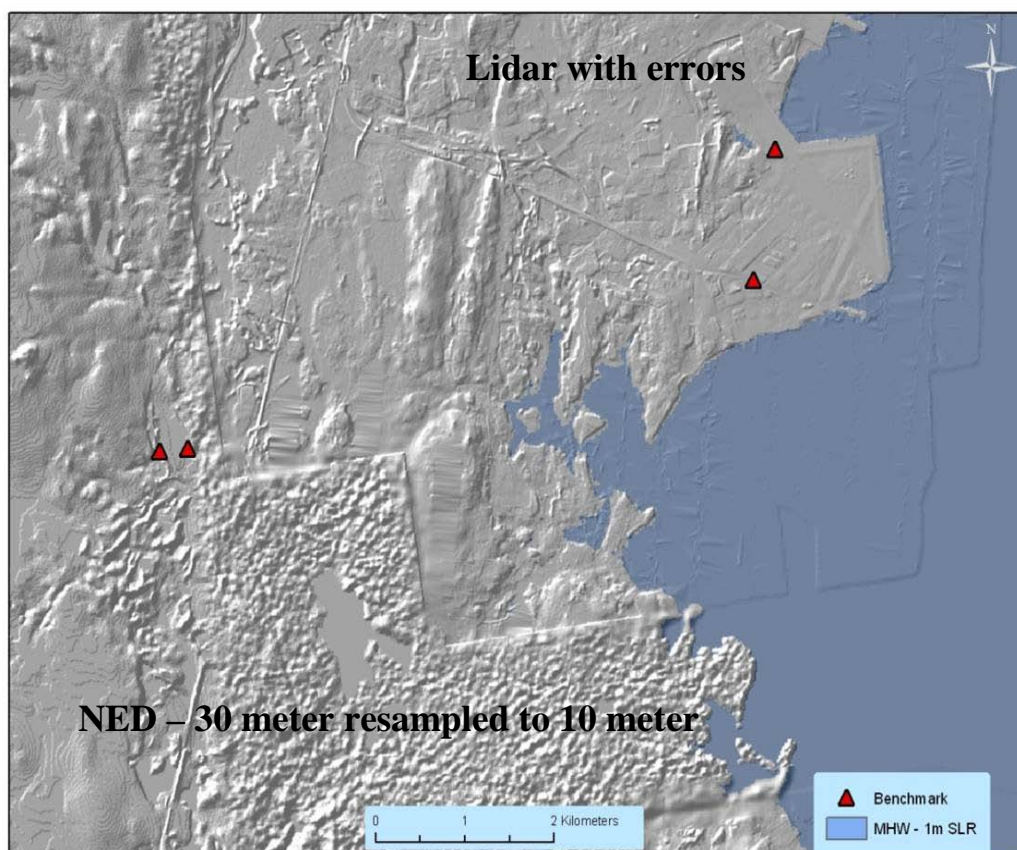


Figure 5. Errors at the seam of two data sets with different vertical accuracies.

Even with the above-mentioned erroneous area included in the integrated data set, the overall root mean square error (RMSE) of the integrated data set proved to be 55% more accurate than the seamless NED. It is important to note, however, that because data integration errors can be masked by accuracy assessments derived from point benchmark data, as we found in our study, we recommend the use of additional accuracy assessment metrics in combination with the benchmark data.

Specifically, additional metrics should be able to assess the quality of the overall integrated elevation data set and especially the quality of the blending procedure. For example, cross-sectional transects could be placed along the seams of data sets that are to be blended together (Figure 6). The cross-sectional profiles of the topography would allow comparisons to be made between the most accurate data set (i.e., lidar) and the integrated DEM (e.g., a mosaic of the lidar and the NED). This additional accuracy assessment metric would also be an effective and rule-based way to determine an appropriate transition zone width for the blending procedure.

Following Gesch and Wilson (2002), blending two disparate elevation data sets requires the identification of a “blending zone” width within which data from each of the two elevation data sets are extracted and interpolated into a new transition zone DEM. The transition zone DEM is composed of elevation values from each of the original disparate DEMs, and overlaps both DEMs within the blending zone.

The overlapping transition zone DEM is combined with the original DEMs using a blending procedure that forces the output cell values of overlapping areas to be a blend of values. Because the identification of a blending zone width can be somewhat arbitrary, transects could also be used as a method to test various zone widths to identify the best-fitting zone width via a coefficient of determination (R^2), which would, similar to above, compare the integrated DEM against the most accurate DEM (e.g., lidar). This approach would allow users to identify varying transition zone widths, depending on the resolution and accuracies of the input DEMs.

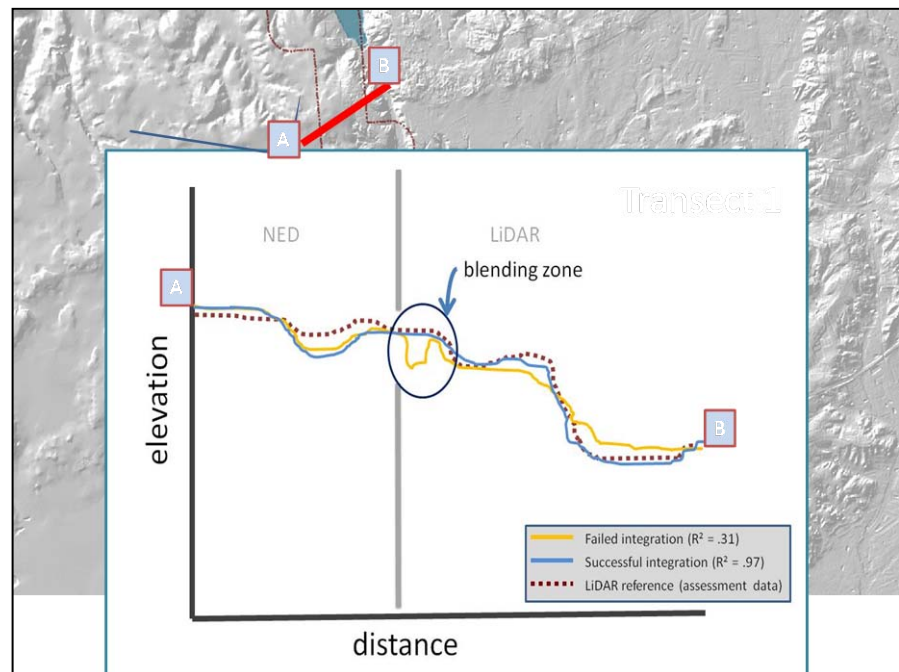


Figure 6. Cross-sectional transect of the seams of data sets to be blended together.

In addition to using an accuracy assessment like the one presented here, we recommend that users inspect the integrated DEM thoroughly to find errors that might occur during the blending process. If there is a lack of a complete metadata record or if the source of the data is not known for an individual data set, we recommend against the use of these data in an integration process with credible elevation data sets.

Significant time, storage space, and processing power, in addition to technical expertise, were required to integrate these elevation data sets. However, this study showed that the methods can be used to improve the best currently available multi-state DEM (e.g., NED). Furthermore, using this methodology, users can update regional DEMs by integrating the most up-to-date and accurate DEMs as they become available. Though this study was tested over a large geographic area, similar methods could also be used for smaller areas where data sets of varying resolutions need to be integrated.

Sea Level Rise Mapping

Topography data sets such as those used in this study are usually collected for land-based applications and are therefore rarely referenced to tidal datums. Because we mapped SLR, transforming the DEMs' datum from NAVD88 to mean high water (MHW) was necessary. Several tools and techniques have been developed to assist with datum transformations, with the most popular being NOAA's VDATUM. Because of incomplete VDATUM coverage (represented as a point database in coastal waters), a single datum conversion value to go from NAVD88 to mean high water (MHW) was calculated by averaging the difference between both NAVD88 DEMs and MHW in the study area where VDATUM coverage existed. Though this likely introduced errors where local tidal ranges vary from the averaged conversion unit, using alternative methods to adjust for local tidal ranges was beyond the scope of this study (for more information on datum conversions see

www.csc.noaa.gov/topobathy/Topographic-and-Bathymetric-Data-Considerations.pdf).

Additionally, it was difficult to accurately model hydrologic connectivity while mapping SLR across our study region due to the abundance of bridges and the time required to appropriately

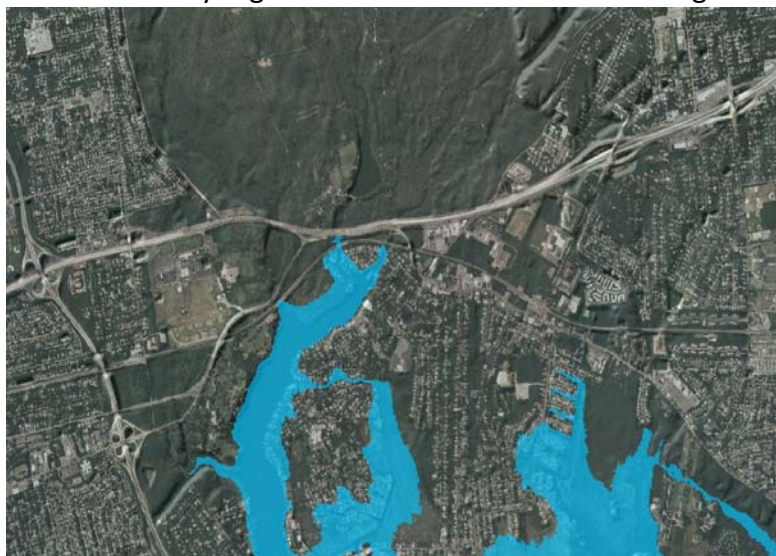


Figure 7. Disconnected stream segments due to lidar barriers.

condition the DEM (i.e., connecting stream segments through bridges picked up as barriers on the lidar) (Figure 7). We were therefore constrained to using the “bathtub” SLR mapping approach, leaving low-lying areas upstream of bridges hydrologically unconnected. Given this constraint, we found that the integrated DEM had 7% less inundation than the NED (Figure 8).

In other words, since the integrated DEM was more vertically accurate, mapping SLR produced less area of inundation.

These findings were expected, since other studies have shown lower-quality elevation data sets to experience higher levels of inundation (Titus and Wang 2008; Gesch 2009). Overall, SLR mapping was more accurate with the integrated DEM, although mapping current mean high water (as “0 meters”) was not possible without additional effort because of interpolation errors that occurred during the blending process.

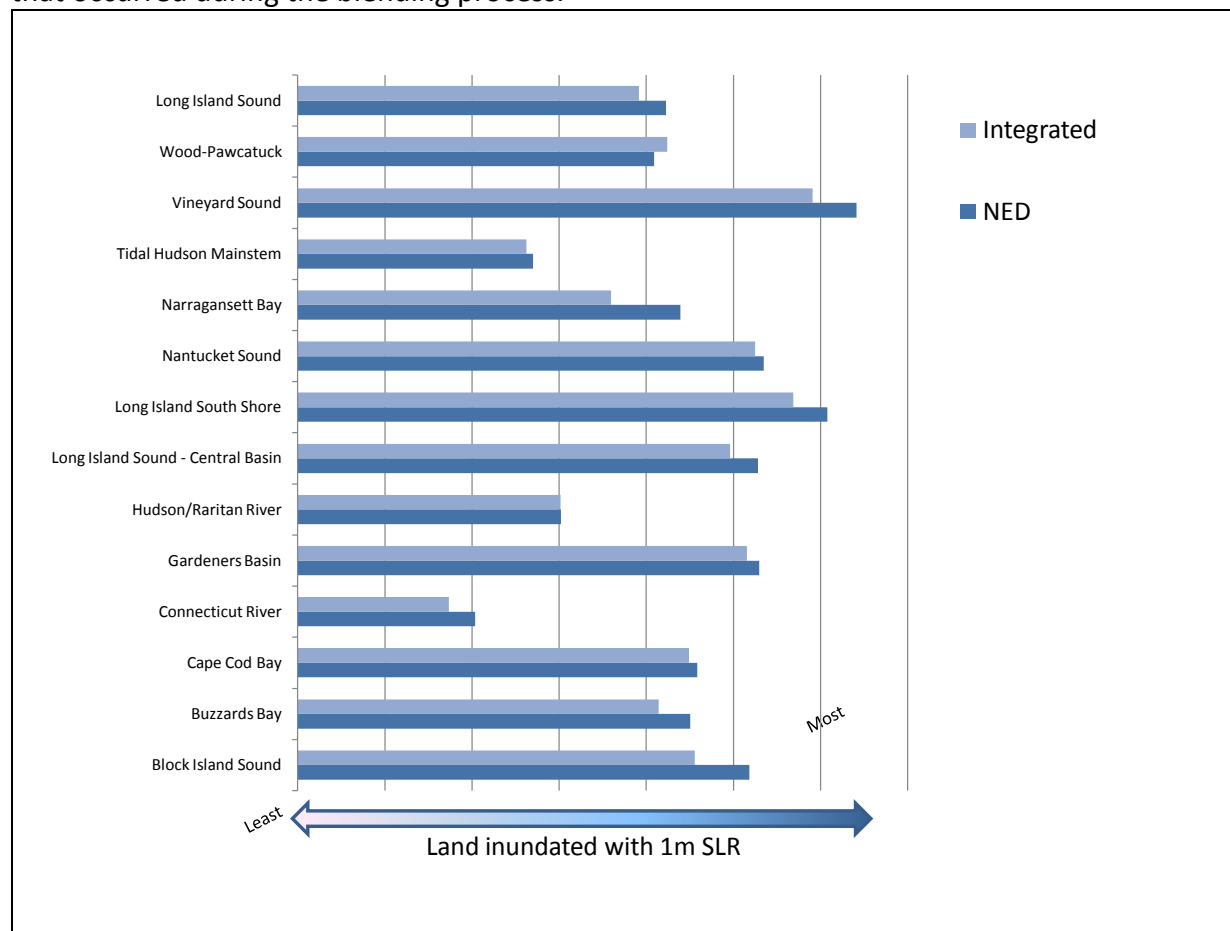


Figure 8. The difference in inundated land between the integrated DEM and the NED for each shoreline unit.

To spatially illustrate the uncertainty associated with mapping a 1-meter SLR, we mapped three inundation zones—high, medium, and low—while incorporating the vertical root mean square error (RMSE) of the elevation data in an effort to give users a transparent picture of the variability associated with these elevation data sets (Figure 9). RMSE is a measure of precision that calculates the differences between values predicted by a model and the values actually occurring in the data set being modeled. The RMSE is the same accuracy metric used for the assessment of the entire conterminous U.S. NED (Gesch 2007) and is described in Maune, Maitra, and McKay (2007).

Gesch (2009) recommends that two inundation zones be mapped as determined by the linear error at the 95% confidence interval in order to spatially illustrate uncertainty. The linear error (L.E.) is the metric used by the National Standard for Spatial Data Accuracy (see Federal Geographic Data Committee 1998 for more information: www.fgdc.gov/standards/projects/FGDC-standards-projects/accuracy/part3/chapter3). These zones are as follows: High = 1-meter SLR + 1.96 x RMSE, and Low = 1-meter SLR - 1.96 x RMSE, respectively, for the 1-meter SLR scenario. Although their approach is certainly more

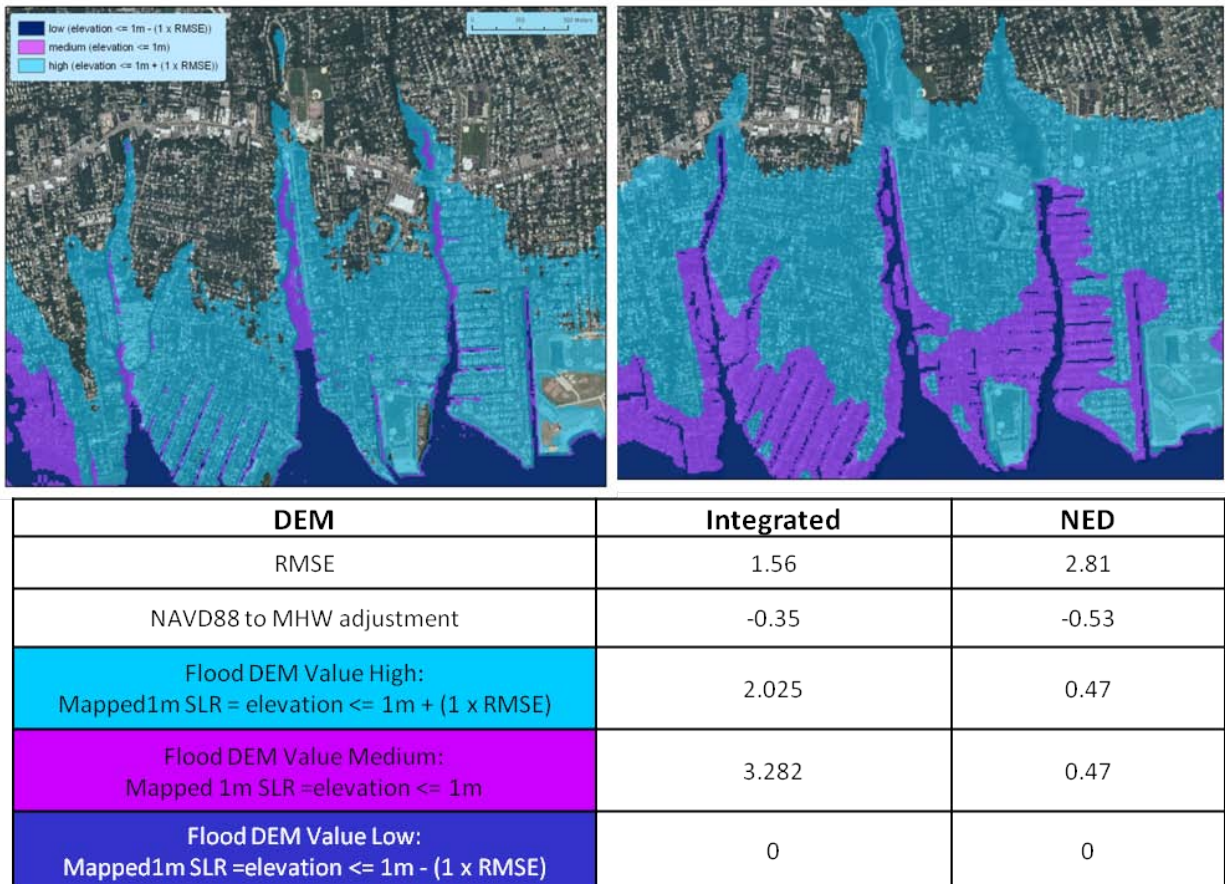


Figure 9. Uncertainty conveyed by mapping high, medium, and low levels of potential inundation (integrated dataset on the left).

cautious, we decided to calculate a third interval using the actual mapped value (e.g., medium = elevation <= 1 meter), in addition to using the high and low extents noted above. This was done to provide a “middle ground” SLR estimate. It should also be noted that error can be introduced during the datum conversion process going from NAVD88 to MHW, and where possible this should be considered here. We modified Gesch’s approach and used the following rules to determine the SLR inundation zones:

- **High** (1-meter) = elevation <= 1 meter + (1 x RMSE)
- **Medium** (1-meter) = elevation <= 1 meter
- **Low** (1-meter) = elevation <= 1 meter - (1 x RMSE)

We should note that if users intend to view or analyze inundation for a specific area, we recommend that they use the single most accurate DEM for modeling SLR and not conduct data integration. This approach would provide the most accurate SLR projection map for that area as it would utilize the most up-to-date elevation data without scaling up high-resolution data to match coarser data. This approach would also allow the illustration of varying inundation uncertainty zones as determined by the underlying elevation data accuracy. For example, there would be smaller uncertainty inundation zones for more accurate data sets and larger uncertainty zones for less accurate data sets, and as users panned from one data set to the next, they would be able to visualize the varying uncertainty contained within the underlying elevation data. Following our rule-based SLR mapping method detailed above, low, medium, and high zones would be calculated based on the RMSE for each individual DEM. This approach would create a transparent and accurate representation of potential inundation for decision makers viewing or analyzing SLR inundation in a specific geography.

In summary, if users intend to perform advanced spatial analyses, we recommend analyzing individual data sets over integrating the most up-to-date and accurate elevation data sets into a seamless, single DEM. However, if a seamless data set is required, we recommend the methods outlined above and urge that multiple accuracy assessment metrics be undertaken to ensure accuracy of the DEM blending procedures.

Regional Approach: Providing a Vision for Local Decision-Making

The present case study was done in two parts, the first of which has been presented. Part 2 of this case study will include the integration of mapped SLR projections, the current distribution of natural resources, the vulnerability of those resources to SLR, and the implications of this analysis for coastal human communities to provide a robust framework for decision-making. Part 2 will feature analyses performed with two additional datasets:

1. Summarize the expected future shoreline protection (e.g., bulkheads, dikes, beach fill) using data from Titus and others (2009) for the entire Southern New England study area. This study estimated shoreline protection scenarios based on 131 state and local land-use plans and a business-as-usual scenario of coastal development.
2. Utilize The Nature Conservancy's Northwest Atlantic Marine Ecoregional Assessment (NAM ERA) to examine the distribution of coastal features targeted for conservation within the study area in relation to expected future shoreline protection and areas of relative vulnerability to 1 meter of SLR. Mapping and analyzing these relationships highlight opportunities where natural communities may be able to help human communities adapt to climate change.

Although examining SLR regionally across states is incredibly valuable for providing spatially explicit information on this global threat, we recognize that the scale at which decisions will have the most significant impact for both human and natural communities is local. Further exploration at more local scales is a natural extension of the work presented in this case study.

For more Information

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